Contemporary Neutron Physics

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"SUCH AN ATOM WOULD HAVE VERY NOVEL PROPERTIES. Its external field would be practically zero, except very close to the nucleus, and in consequence it would be able to move freely through matter. Its presence would probably be difficult to detect with the spectroscope, and it may be impossible to contain it in a sealed vessel. On the other hand, it should enter readily into the structure of atoms. . . ." Such was Rutherford's prediction (*21*) of the properties of atoms with zero nuclear charge, 12 years before they were discovered and became generally known as neutrons. In the 1930s they rapidly established their reputation as fascinating experimental subjects, but were little known outside of

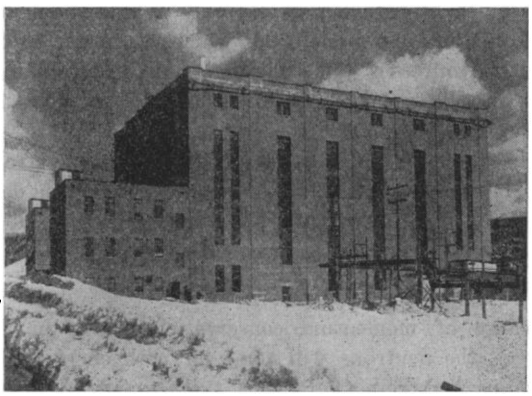

Fig. 1. Building housing the reactor of the National Research Council of Canada at Chalk River, Ontario.

nuclear physics laboratories. The closing days of the war revealed them dramatically as the business of men at large and the basis of big engineering projects (Fig. 1; courtesy National Film Board), for they were disclosed as the dynamic agents of nuclear reactors and atomic bombs. Yet this emergence into the headlines has not detracted from their continuing fascination as laboratory subjects; much is still being learned about their interaction with matter and about their properties as elementary particles.

Neutron Cross Sections; Neutron "Spectrometry"

The biggest single subject in neutron physics is the study of the nuclear cross sections for various processes and their variation with the neutron energy. A "cross section" in this sense is the effective target size which the nucleus presents to the approaching neutron; the latter is considered to be a point. If all cross sections were just the geometrical sizes of the nuclei, their measurement would be dull indeed. Actually, this is far from the case, for resonance and other effects introduce such enormous variations that the study becomes very colorful. The slow neutron capture cross section of Gadolinium 157, for example, is 4×10^4 times larger than its geometrical cross section. On the other hand, Nitrogen 15 has a capture cross section less than 10^{-7} of its geometrical cross section—which is merely a technical way of saying that it stubbornly refuses to capture slow neutrons. The Gadolinium 157 cross section is at least 10^{12} times larger than that of Nitrogen 15! This astonishing range of magnitude has important practical consequences in such matters as nuclear reactor design. Here a new scale of values of structural materials has sprung up; if a suggestion is made as to a new substance for use as part of a reactor, the first question asked is not "What is the tensile strength?" or "What is the cost?" but rather "What is the cross section?" Clearly, the cross sections for various processes are fundamental to any quantitative treatment of the interaction of neutrons with matter. They are also the most frequent meeting ground of experiment with nuclear theory.

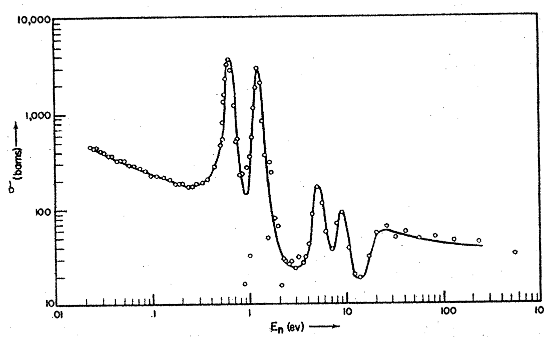

Fig. 2. The slow neutron absorption spectrum of Iridium as measured by the Columbia University neutron spectrometer group (from H. H. Goldsmith, *et al. Rev. mod. Phys.*, 1947, 19, 291). The rise to the left is tpical of the 1/v part of the spectrum, and the peaks are neutron capture resonances.

The variability in absolute magnitude of the slow neutron capture cross sections is accompanied by unpredictable fluctuations in the cross sections of individual nuclear species as the energy of the incident neutrons is changed (Fig. 2). Characteristically, the absorption spectrum consists of two parts: (1) In the low-energy range (perhaps up to a few electron volts) the capture cross section is inversely proportional to the neutron's velocity v (*i.e.* directly proportional to the time spent by the neutron near the nucleus), while (2) above the 1/v region there are a number of irregularly spaced peaks, some of which may be astonishingly high. There are exceptions to this general picture. In some cases the peaks may be missing so that the 1/v region is visible to higher energies, and in other cases the peaks may invade the 1/v region to below thermal energies. The peaks are accounted for in the Breit-Wigner theory (1936) as maxima which occur when the energy of the incident neutron is such as to place it in resonance with an energy level in the compound nucleus formed upon capture. As such, the neutron resonances give us information about the spacings and widths of nuclear energy levels.

A great deal of cross-section work is being done with simple transmission experiments or elaborations thereof. A neutron detector is placed some distance from a source, and an absorber is placed between the two. The attenuation of the neutron beam reaching the detector is then proportional to $e^{-Nx\sigma}$, where N is the number of atomic nuclei per cm^3 of absorber, x is the thickness in cm, and σ is the nuclear cross section which is effective for removing neutrons from the beam. This removal can be accomplished either by direct absorption of the neutrons into the nuclei of the absorber or by nuclear collisions which result in the scattering of the neutrons from the beam. The cross section can accordingly be divided into two parts: $\sigma = \sigma_{abs} + \sigma_{scatt}$. σ_{scatt} can in principle be measured independently by placing a detector at various points to the side of the main beam and determining how many neutrons are deflected by the presence of the scattering object. A natural extension is to measure carefully the variation with the angle of scattering. This is of fundamental importance in such cases as the scattering of neutrons by hydrogen, because the results are then significant to our understanding of the short-range neutron-proton forces. It is often possible to measure σ_{abs} independently by the strength of the radioactivity induced by the neutrons in the absorber, and σ_{scatt} can then also be determined by difference: $\sigma_{scatt} = \sigma - \sigma_{abs}$.

This type of experimentation is clearly very simple in principle. Actually, it is the desire to know the variations of σ with neutron energy which introduces the complications and calls for experimental ingenuity. The problem of making a source which emits neutrons of a single energy is being met in a variety of ways. One of the simplest is the use of photoneutron sources. It happens that two materials, deuterium and beryllium, can be persuaded to release neutrons by the action of gamma rays of quite modest energy; in fact, the (γ,n) threshold of beryllium is 1.63 Mev, and that of deuterium is 2.18 Mev. It also happens that nuclear reactors and cyclotrons can make a dozen or so radioactive substances which emit gamma rays with energies greater than 1.63 Mev. For example, one can place sodium in the nuclear reactor overnight and in the morning have a powerful source of 2.76 Mev gamma rays from Sodium 24. If this radioactive sample is then placed in a lump of beryllium, neutrons will emerge, and they will all have an energy of $2.76 - 1.63 = 1.13$ Mev (provided the beryllium lump is not large enough to degrade the gamma rays or to slow down an appreciable number of the neutrons by nuclear collisions). Likewise, if the sodium is placed in heavy water, neutrons with an energy of 0.58 Mev will be produced. In either case, transmission, absorption, and scattering experiments can be made in any desired substances and values of σ_{abs}, σ_{scatt}, and σ obtained for neutrons of these energies. A survey of cross sections measured in this way has recently been made at the Argonne National Laboratory (*10*). Inasmuch as nature provides only a limited number of combinations of materials which can make photoneutron sources of this kind, the results to be obtained can only be rather spotty in terms of a study of the variation of the σ's with energy.

A classical source of monoenergetic fast neutrons has been the so-called "D-D" source, in which deuterium is bombarded with deuterons in a high-voltage machine. The reaction concerned is

$$_1D^2 + {_1D^2} \rightarrow {_2He^3} + {_0n^1} + 3.31 \text{ Mev}.$$

Because of momentum conservation effects in the target, the neutrons will come off with energies depending on their angle with the primary deuteron beam. Together with variation of the beam voltage, this sensitivity to angle can be used as a means of varying the neutron energy. Neutrons below about 1.5 Mev are, however, unobtainable. Partly because of this handicap, it has been more usual recently to use the Li(p,n) reaction in electrostatic generators as a source of neutrons of moderate and controllable energy. The reaction is

$$Li^6 + p \rightarrow Be^7 + n - 1.62 \text{ Mev}.$$

Below 1.62 Mev no neutrons are observed. As the energy of the protons is increased above the threshold, neutrons are emitted and their energy depends upon the voltage and upon the angle of emission from the target relative to the incident proton beam. The energy spread of the neutrons depends upon the thickness of the lithium target and upon the steadiness of the voltage; therefore, the targets usually are very thin lithium films, vacuum-evaporated *in situ* upon a heavy metal backing, and the voltage is stabilized with high precision by automatic devices. This kind of monokinetic neutron source has been the basis of a number of important light-element cross-section studies made at Los Alamos. The energy range covered is approximately from 0.05 to several Mev.

The 184-inch cyclotron at Berkeley has turned out to be a unique source of very fast neutrons, and it is ideally adapted for cross-section measurements in the region of 100 Mev. The neutrons emerge from the target in a well-defined beam, the origin of which is in itself interesting (*15*). Let us consider what happens when a high-speed (190-Mev) deuteron passes near a target nucleus. The neutron and the proton have internal motion about their common center of gravity in the deuteron. If the proton should happen to be closer to the target nucleus at the moment of passing, it is possible that it will stick in the nucleus. The neutron will then carry on with a velocity and direction determined by the vectorial addition of its motion in the deuteron and its motion in the cyclotron beam. At 190 Mev, the latter is by far predominant. The neutron beam therefore shoots out in the direction that the cyclotron beam had when it struck the target. It has an angular spread of a few degrees, and an energy spread of about 40 Mev which arises from the fact that the neutron's velocity internal to the deuteron could either add to or subtract from the velocity in the cyclotron beam. The neutron beam passes through the vacuum chamber wall and is conducted through a pipe set in the thick concrete shield surrounding the cyclotron, and it is thus available for experimentation in the surrounding laboratory space. Of course, a similar beam of protons is simultaneously made when the neutrons, instead of the protons, are stripped from the deuterons by the target nuclei, but it is swept aside because the protons, being charged, are still subject to the forces of the cyclotron's magnetic field.

One of the studies made with this neutron beam was concerned with the variation of σ_{scatt} with the atomic weight A of the scatterer. Earlier, a similar study (*22*), made with 20-Mev neutrons from the old Harvard cyclotron, had shown that σ_{scatt} was proportional to $A^{2/3}$. The σ_{scatt} so measured was, in fact, a good measure of the geometrical cross section of the nucleus; this is one way to measure the size of nuclei. The results from the Berkeley survey with 90-Mev neutrons (*7*) showed a similar smooth increase of σ_{scatt} with A, but the σ_{scatt}'s measured at Berkeley were all *smaller* than those measured at Harvard. This is interpreted as evidence of a partial transparency of nuclear matter to the neutrons of higher energy. The wave length of the 90-Mev neutrons (3×10^{-13} cm) is comparable with the nuclear dimensions, and the probability exists that the neutron can slip through the nucleus without being deflected. Apparently, even nuclear matter, by far the densest known, has some Swiss-cheese characteristics when viewed by appropriate means.

Let us jump now from the very fast neutron field to the slow neutron field. The latter is generally taken to cover the energy range below about 100 ev. Here we find that the experimental tools are again different and that the data are much more complete. One method of attack is that of crystal spectrometry. Since this has itself been the subject of a recent article in *Science* (*23*), we shall simply state here that in the energy range of a few electron volts the neutrons have wave lengths comparable to the lattice spacings of atoms in crystals, and therefore they exhibit Bragg reflection just as do X-rays and electrons. Thus, if a narrow beam of slow neutrons of mixed energies is allowed to fall upon a crystal at an appropriate small angle, at another appropriate small angle there will be found a beam of monokinetic neutrons coming from the crystal. One therefore makes transmission measurements at various angular settings in order to cover the available energy range. Since this type of work practically demands the intense, steady, slow neutron beams which are obtainable only from nuclear reactors, it is in progress mainly at the Argonne and Oak Ridge National Laboratories.

By far the greater part of the slow neutron spectrometry has been done by means of the "time-of-flight" method. This method is based upon the fact that it takes quite a respectable time (e.g. 1 millisecond) for a slow neutron to cross a room. If a neutron source on one side of the room is made to emit a short, sharp pulse of neutrons (of unavoidably mixed energies), and if the detecting apparatus on the other side of the room is made sensitive for an equal interval *at a relatively long time, t, later,* then clearly only the neutrons which took about t seconds to cross the room will be counted. The neutron energy range can be covered by varying t, although the resolution becomes poor above 100 ev because t then becomes almost as short as the duration of the pulses. One simple apparatus which works on this principle is the velocity selector at the Argonne Laboratory (*8*). A cadmium shutter rotates in a beam of slow neutrons emerging from a nuclear reactor. Since the cadmium absorbs slow neutrons completely, a chopped beam results. A mirror mounted on the rotating mechanism flashes a light signal to the detecting equipment, which is then electronically sensitized for the appropriate interval. The time, t, is determined by the angular displacement of the mirror relative to the cadmium on the rotor. Mechanical choppers of this kind have their main usefulness in the energy range below about 0.1 ev.

The time-of-flight measurements have come to full flower in connection with cyclotrons. Cornell and Los Alamos have contributed in the past, but the most consistent and sustained efforts have been made at Columbia (*20*). In an important series of papers in the *Physical Review,* the Columbia group have described measurements of the neutron cross sections of nearly all of the elements in the energy range 0.015–1,000 ev. Fig. 2 is a reproduction of one of their curves which may be considered typical.

The reader may have noticed that in our discussion we have left an energy gap covering, roughly, the region 1,000–50,000 ev. This region has been difficult to deal with experimentally, partly because detectors become relatively insensitive and partly because of the difficulties of finding suitable sources. The gap is now being closed. Refinements in the Li(p,n) technique are reducing it from the high-energy side, and important improvements in the Columbia apparatus are closing it from the low-energy side. It is true that the resolution obtainable in this difficult region remains rather poor, but the results are, nevertheless, significant. A pretty example of a fairly complete cross-section curve is that of aluminum, published in a recent compilation of cross-section data which appeared in the *Reviews of Modern Physics* (*11*). This curve covers the energy range from 0.001 to 1.0 Mev and shows a group of prominent resonances in the hundreds-of-kilovolts region.

Scattering Resonances

We have spoken of the peaks in the cross-section curves (Fig. 2) as being almost entirely due to absorption. The Breit-Wigner theory recognized, however, that they might be accompanied by especially prominent scattering; in fact, some of them might be almost entirely due to scattering, particularly in the hundreds- to thousands-of-electron-volts region. The existence of these scattering resonances has recently been experimentally demonstrated at the University of Illinois and at the Argonne Laboratory. In the experiments at the Argonne Laboratory a number of elements have been surveyed. Cobalt is typical of those which gave a positive result. A neutron beam from the reactor was passed axially down an evacuated tube which formed the inner wall of a double-walled cylindrical counter, the annular space of which was filled with BF_3 gas. Ordinarily there would be no counts registered in the BF_3 because there would be nothing to deflect neutrons from the beam into the sensitive region of the counter. However, when a thin cobalt foil was placed in the middle of the apparatus, the whole assembly became a detector sensitive to neutrons which are scattered by cobalt. Another cobalt foil was then placed in the neutron beam some distance ahead of the counter, and the transmission of this foil was measured as it appeared to this very specialized detector. The effective σ thus found was much higher than it would have been if the foil in the detector had been something other than cobalt or if the foil in the detector absorbed, rather than scattered, the neutrons falling upon it. The demonstration of a scattering resonance was therefore clear. The average neutron energy in the primary beam was varied somewhat by interposing different thicknesses of boron in order to absorb different proportions of the slow neutron component, and in this way the scattering was identified as arising from a resonance at 115 ev, previously found by the Columbia cyclotron group.

A similar result was obtained for a 300-ev resonance in manganese, and a survey of elements gave indications of resonance scattering from a number of medium-light elements—predominantly from isotopes of odd mass number (*12*).

Slowing Down and Diffusion of Neutrons

The nuclear reactions which give rise to free neutrons nearly always produce them with energies of the order of millions of electron volts. Since many of their most striking properties appear when they have energies of hundredths of one electron volt, the mechanism of slowing them down becomes one of importance. The slowing down is accomplished by allowing them to pass through matter where they lose energy by nuclear collision processes. If the nuclei are heavy, there is energy loss by inelastic collisions, *i.e.* some of the neutrons' kinetic energy is used to excite the nuclei to states which they later leave by means of gamma-ray emission. For light nuclei the energy loss arises mainly from elastic or billiard-ball collisions.

Application of the ordinary laws of conservation of momentum and energy to the elastic collisions shows that, on the average, the ratio of the energy of a neutron after impact to its original energy is a constant depending only upon the mass of the nucleus struck; in other words, the percentage loss in energy per impact is constant or, again, the mean logarithmic energy loss ξ is a characteristic of the medium. For example, for graphite, $\xi = 0.16$, and it follows that it takes about 110 collisions to slow a neutron from 10^6 ev down to 1/40 ev. In hydrogen (by far the most efficient slowing-down agent), $\xi = 1$, and 17 collisions suffice, on the average, to give the same energy reduction.

After neutrons are slowed down in a medium they diffuse around until they are captured by nuclei or escape from the boundaries. Neutron diffusion theory gives the density distribution of the neutrons in the medium, and direct comparison with experiment is easy. In its formulation, the diffusion theory is strongly reminiscent of classical heat-flow theory, with its sources and sinks and solutions of second-order partial differential equations through Fourier series, and its application of physical boundary conditions in the evaluation of the mathematical arbitrary constants. A typical solution is that of a rectangular parallelepiped with a source uniformly distributed over the end; in this case the neutron distribution some distance from the source plane is a negative exponential along the axis away from the source, and a cosine in the two transverse directions, with the maximum on the axis.

Present research lies mainly along the direction of introducing refinements in the theory and in its comparison with experiment. The substitution of "transport theory" for the older, less exact theories is an example. Transport theory takes into account the fact that for light elements there is a persistence of motion in the forward direction following elastic scattering collisions. On the experimental side, we may cite a current diffusion experiment at Oak Ridge in which the slowing-down theories are being tested with a photoneutron source buried in graphite. Such an arrangement lends itself to easy calculation, for the neutrons are initially monokinetic and the source is essentially a point.

Magnetic Properties of Neutrons; Neutron Polarization

Despite its lack of electric charge, the neutron has been found to have a magnetic moment. The measurement of this moment has been the subject of some rather elegant experimentation, but we shall forego a description of that in order to discuss the field of investigation which is opened by the mere *existence* of the moment. The point is that the magnetic moment gives us a grip upon neutrons whereby their orientation in space can be controlled. Consider a beam of slow neutrons passing through a block of iron. Their spins, and therefore their magnetic moments, will be randomly oriented in space, as also will be the magnetic moments of the iron atoms which they encounter. There will, however, be some interaction, and this results in some scattering of the neutrons. It will be noted that this is not a nuclear effect; the magnetic moment of the iron atoms is electronic in origin, and the magnetic forces between iron atoms and neutrons are much weaker, but of longer range, than the forces involved in scattering by direct nuclear collision. Anyway, the next step is to suppose that current is turned on somewhere in a coil, and the iron block becomes magnetized within 0.1% of saturation. The magnetic domains in the iron come to attention and line up with their moments co-directional in the field. The neutrons also straighten around so that their spins are either parallel or antiparallel with the field. There is now some coherency in the magnetically scattered waves. The interference of these waves with those arising from the purely nuclear scattering formed the basis of a prediction (1936) of an observable selective scattering effect. The prediction, which has been amply confirmed by experiment, was that those neutrons whose moments are aligned parallel to the imposed field will have an effective cross section $(\sigma_o - p)$ for scattering which is appreciably smaller than the cross section σ_o, which holds in the absence of the magnetic field. Such neutrons accordingly will be preferentially transmitted through the iron block. Simultaneously, the neutrons which had their moments aligned antiparallel with the imposed field will be scattered *more* efficiently than they were before the iron was magnetized (cross section: $(\sigma_o + p)$; consequently, the transmitted beam will be depleted in these neutrons. Because of the exponential character of the attenuation of the beam, these two effects do not exactly counterbalance; there is a net increase in the intensity of the total transmitted beam when the iron becomes magnetized. The percentage increase is called the "single transmission effect"; it is easily observed, and its magnitude is a measure of the degree of polarization in the beam of transmitted neutrons.

In the older work, the single transmission effect amounted to a few per cent, but it has recently been shown at the Argonne Laboratory (*16*) that the modern, powerful slow-neutron sources, plus some refinements in technique, permit the use of iron blocks up to 9 cm thick, with resultant single transmission effects of 100%. In such a beam, about 80% of the neutrons have their moments lined up parallel with the magnetic field and 20% antiparallel. Of course, this degree of polarization is purchased at the cost of a large reduction in intensity. The value found for the magnetic scattering cross section, p, is 3.15 barns.[1] With σ_o equal to only 11 barns by itself, it is clear that the influence of the magnetic field upon the scattering is quite considerable.

What one would *like* to do with these polarized neutrons is to direct them against nuclei which are themselves lined up in space, and so measure the effects of the spin-dependent forces upon scattering, capture, fission, etc. It is the difficulty of lining up the target nuclei, rather than the neutrons, which at present is retarding the start of this kind of work. Meanwhile, the polarized neutrons are finding other

[1] One "barn" $= 10^{-24}$ cm^2.

fields of usefulness. It turns out, for example, that the depolarization caused in a beam of such neutrons by a passage through a thin sheet of steel is related to the size of the microcrystals in the steel. Thus, if two magnets are set up in a polarizer-analyzer combination, the thin sheet can be placed between them and the depolarization can be measured (*5*). Thus, the relationship between metallurgical treatment and microcrystal sizes in steel can be evaluated by a new method. The future will probably see a broadening use of neutrons in studying many such nonnuclear properties of matter.

Search for Specific Interaction between Neutrons and Electrons

In the last section we discussed some of the consequences of the magnetic interaction between neutrons and atomic electrons, in so far as the influence upon scattering was concerned. Two recent experiments (*9, 13*) have been carried through in search for a new kind of electron-neutron interaction *independent* of spins and magnetic moments. Since the underlying concepts are interesting, we shall briefly describe one of the experiments (*9*) here.

According to the provisional probings of current meson theory, neutrons are not always solidly packed, neutral elementary particles. They may oscillate very rapidly between such a state and a state consisting of a proton with a negative meson about 10^{-13} cm away; in fact, they may spend as much as 20% of the time in the latter state. If this were the case, on a time-average basis there would be a net electric field very close to the neutron. According to the following reasoning, this might be observable as a slight asymmetry in the scattering of slow neutrons: the nuclear scattering is spherically symmetric in the center of gravity system because the scattering object is small compared with the wave length of the incident neutrons (about 10^{-8} cm). The atomic electrons, on the other hand, are arranged over distances comparable to the wave length of the incident neutrons, and if they *could* interact with the neutrons, they would produce an asymmetric scattering. The effect to be observed would arise from the interference of the two kinds of waves. The asymmetry would persist and, if found, would be indicative of the existence of a neutron-electron force field. Only a small effect would be expected, but there was always the possibility that the present formulation of the meson theory might have led to an underestimate.

In the experiment, xenon gas was chosen as the scatterer because (1) its closed electronic shell structure insures the absence of magnetic scattering, and (2) its monatomic gaseous nature insures the absence of any scattering arising from arrayed atoms. A beam of slow neutrons was directed through a vessel containing the xenon, and two counters were set up in order to detect neutrons scattered, respectively, at 45° and 135° with respect to the direction of the beam. Background counting rates were determined by freezing out the xenon. After the application of corrections to a series of observations, the net relative difference in the counting rates in the two directions turned out to be -0.0005 ± 0.0085. Apparently, the electron-neutron forces do not show up like a ton of bricks. In the cautious words of the experimenters: ". . . no interaction of an order of magnitude larger than that predicted by the meson theory exists between neutron and electron."

Delayed Neutrons

Another aspect of neutron physics which is arousing current interest is the phenomenon of delayed neutron emission. Originally discovered in connection with uranium fission, the delayed neutrons are the result of special circumstances in beta radioactivity. A highly beta-unstable nucleus may, after emission of its beta-particle, remain in a state of considerable excitation. Ordinarily this energy appears as gamma radiation accompanying the beta decay. However, it may happen that the excitation is greater than the energy corresponding to the binding of a neutron in the residual nucleus. If this occurs, a neutron is emitted in preference to gamma radiation. Consequently, we have the appearance of "neutron-emitting radioactivity" with half-lives and chemical behavior identical with those of the preceding beta transitions. The fission product nuclei, Bromine 87 and Iodine 137, have been identified as those responsible for two delayed neutron activities, with half-lives of 55 and 22 sec, respectively. Recent developments in the laboratory of the large cyclotron in California have shown that an additional nucleus, Nitrogen 17, producible by bombardment with 190-Mev deuterons, is a delayed neutron emitter (*4*). The half-life is 4.4 sec. The half-lives of delayed neutron activities are characteristically short, because of the implied high beta instability of the parent nuclei.

The identification of the fission-product emitters, Bromine 87 and Iodine 137, has a little story associated with it which is interesting because the identifications tie in very neatly with some recent ideas in nuclear structure. The initial tentative identifications were made in the face of rather serious theoretical objections. These objections arose from the fact that these isotopes are both very close to stability. It should be noted that after beta emission, Bromine 87 becomes Krypton 87 and Iodine 137 becomes Xenon 137; it is the Krypton 87 and the Xenon 137 nuclei which actually emit the delayed neutrons. Yet the isotopes Krypton 86 and Xenon 136, *just one mass unit below*, are completely stable. It would have been much more probable that the delayed-neutron emitting isotopes should have been, say, Krypton 91 and Xenon 141, both because the beta instability would be greater and because the neutron-binding energy would be smaller. In spite of these considerations, the first identifications were tentatively made (*24*), and these were later confirmed (*26*). Now it has recently been observed (*19*) that nuclei which contain, respectively, 50 or 82 neutrons are especially stable. The evidence comes from several directions; for example, more different stable isotopes (Xenon 136 through Samarium 144) contain 82 neutrons than any other single number of neutrons, and the second in rank are the stable nuclei which contain 50 neutrons (Krypton 86 through Molybdenum 92). Also, the natural abundances of the 50- and 82-neutron stable isotopes are exceptionally high in comparison with others in like situations with regard to the main line of stability in the isotope chart. Finally, the capture cross sections of the 50- and 82-neutron stable isotopes for both slow and fast neutrons are abnormally low compared with those of their neighbors. Apparently, something has become satiated in these nuclei; another neutron is definitely *non grata*.

Now we observe that Krypton 87 and Xenon 137 have, respectively, just 51 and 83 neutrons in their structure. It is apparently just that last neutron which is lightly bound to the nucleus, and in the presence of quite slight excitation the nucleus lets it go. Similar considerations hold with regard to the new delayed neutron emitter, Nitrogen 17. Beta emission leads to Oxygen 17, which, in a state of excitation, might easily lose a neutron to become the tightly bound Oxygen 16. One might predict on this basis that Boron 13 might also carry delayed neutron activity, although, if so, it probably would have been revealed in the Berkeley bombardments unless its half-life were very short.

Neutrons in the Atmosphere

Cosmic-ray researchers have known for years that free neutrons exist in the atmosphere and that their concentration increases with altitude. An estimate (*14*) on the fast-neutron flux gives several hundred per square centimeter per day at an altitude of 10,000 feet. The fast neutrons are accompanied by neutrons which have been slowed down by collisions in the air, and the latter presumably disappear mostly by capture in nitrogen. It is generally thought that the neutrons are secondary particles, originating from the nuclear explosions which are evidenced by "stars" found in photographic emulsions. Proton tracks are frequently found in the "stars," and it would be peculiar if neutrons (which would make no emulsion tracks) were not emitted in the same events approximately as abundantly as the protons. This mechanism for the origin of the fast neutrons is borne out in a rough quantitative way by a comparison of the numbers of fast neutrons and of star protons, allowance being made for their difference in range in the atmosphere. Another argument for a secondary nature of the neutrons is that they are presumably radioactive, and they therefore would not live long enough to arrive at the earth from the outer regions of space; however, so far as this argument goes, some could perhaps come from the sun.

Fairly complete data on the distribution of fast and slow neutrons as a function of altitude have been obtained by Los Alamos workers by means of counters carried aloft in B-29 aircraft (*1*). The experiments covered the range 10,000–36,000 feet. The counting rates increased uniformly with altitude, doubling for approximately every 8 cm of mercury reduction in barometric pressure. This rate of variation is also that of the total cosmic-ray ionization, produced mainly by the soft component—a fact which also argues for the secondary nature of the origin of the neutrons. Now it is well known that the curve for the ionization arising from cosmic radiation reaches a peak at high altitudes; above the height corresponding to a barometric pressure of 7 cm of mercury the ionization drops again abruptly. If the neutrons are really secondary in origin, they should also show this peak. Curiously enough, the rather fragmentary data so far obtained in balloon flights to extreme altitudes (*17*) show, at most, a flattening off of the neutron counting rate at heights corresponding to barometric pressures of 5 and even 2 cm of mercury. If there is a maximum, it is therefore apparently much higher than is to be expected. One might think that this means that some or all of the neutrons found at that height come either from outer space or from some cosmic-ray component which generates them near the very top of the atmosphere. On the other hand, it is pointed out (*14*) that the position of the neutron maximum is determined primarily by the distance through which neutrons go in the course of being slowed down, and this distance would place the maximum at the lower altitude, even if the neutrons were all made at the most extreme heights. The conflict is therefore between experiment and diffusion theory, rather than between experiment and the postulated source. If there were an especially good slowing-down agent in the composition of the atmosphere at great heights (e.g. water vapor), or if the neutrons were born with, on the average, only a few hundred kilovolts of primary energy, then the conflict could be resolved; however, neither possibility seems likely.

Other Consequences of the Wave Properties of Neutrons

We have already mentioned neutron crystal spectrometry and dismissed it as a subject which will be dealt with lightly here. While it is, nevertheless, the most important field in which the wave properties of neutrons are directly exploited in the laboratory, there are two other manifestations which are rather pretty and which deserve mention. One of these is a trick for obtaining a pure beam of ultra-slow neutrons (*3*). Suppose there is a large block of graphite, say a 4-foot cube, in which thermal neutrons are diffusing. The neutrons will have a Maxwellian distribution about a most probable velocity of 2,000–3,000 m/sec (which corresponds to thermal energies at room temperature), but there will be a few in the distribution with much higher velocities and a few with very low velocities. Now suppose the graphite block to be covered with sheet cadmium so that none of the neutrons become nuisances by emerging into the room, and further suppose that a 4×4 inch hole is cut in the cadmium near the center of the top face. Now let us stand a 4×4 inch piece of graphite on this hole, so that it makes a chimney about a foot high. The sides of the chimney may be covered with cadmium, but the top must be left uncovered. Now consider what happens to the neutrons which enter the base of the chimney. Those with thermal energies or higher can suffer Bragg reflections from the crystals in the graphite, as can be seen by putting numbers in the Bragg relation, $\lambda = 2d \sin \theta$. Here the wave length, λ, of thermal neutrons is around 2 A, and the lattice distance, d, is 3.3 A in the graphite crystals. Clearly, there will be a range of values of λ up to 6.6 A, for which there are Bragg angles, θ, appropriate to crystal scattering. Neutrons with these wave lengths will very probably be scattered sideways in the graphite chimney and will be swallowed by the surrounding cadmium. On the other hand, the crystal scattering is impossible for neutrons with wave lengths greater than 6.6 A, and these neutrons are consequently preferentially transmitted. Thus, the crystal effects enable the chimney to act as a filter whereby all but the very slowest of the neutrons in the large graphite block are removed from the mixture. The transmitted neutrons have energies corresponding to thermal energies at about 18° K and can be used for special experimental purposes. Because of intensity considerations, it is practically essential to use a nuclear reactor for the primary neutron source; our hypothetical cadmium-covered graphite block then becomes one of the "thermal columns" which are customarily built into the concrete shields of reactors.

Our second wave effect occurs at the other extreme of the energy scale. It concerns ultra-fast neutrons and the Fraunhofer diffraction of their waves by nuclei. The case under consideration is that of the diffraction of plane waves by an opaque disc or sphere. Physical optics says that there should be a bright maximum in the center of the "shadow" of the object, and that this maximum should be surrounded by rings of alternating maxima and minima of radially dimishing intensity. The results are conditional upon the wave length of the light being smaller than the radius of the opaque object. This condition is fulfilled very well in the case of the 90-Mev neutron beam from the Berkeley cyclotron, for the neutron wave length is considerably smaller than the dimensions of any but the smallest nuclei. In the experiments (*18*) spheres of aluminum, copper, and lead were placed in the fast neutron beam, and detectors were placed at positions making angles at the sphere of 3°–30° with the direction in which the beam was going. The detectors were graphite blocks, which are sensitive to fast neutrons by virtue of the 20 min Carbon 11 activity induced by the reaction $C^{12}(n,2n)C^{11}$. The central diffraction maxima were strongly present, and the theory was further corroborated, in that the smaller opaque objects (aluminum nuclei) gave a broader diffraction maximum than did the larger opaque objects (lead nuclei). It is true that the lesser maxima and minima were not convincingly observed, but it is, nevertheless, clear that some of the laws of physical optics were here being corroborated on a scale some 10^8 times smaller than that of the classical light experiments.

Radioactive Decay of the Neutron

The first accurate value of the mass of the neutron was obtained in 1935. The result showed that the neutron is appreciably heavier than the proton, and it was immediately suggested (*6*) that neutrons should be beta radioactive in common with other nuclei under like circumstances. Modern values of the neutron-proton mass difference indicate that the beta-particles should have an upper energy limit of 0.75 Mev, and beta-decay theory says that the associated half-life should be about ½ hr. This prediction has since remained on the books as a challenge to the experimentalists. A start on the problem was made at Berkeley (*2*), but the work was interrupted by the war. A new attack is now in progress at the Oak Ridge National Laboratory (*25*). A collimated beam of neutrons (mostly slow) is taken from a hole in the shield of the nuclear reactor and is allowed to pass axially through a horizontal, cylindrical tank which is highly evacuated (Fig. 3). The beam enters and

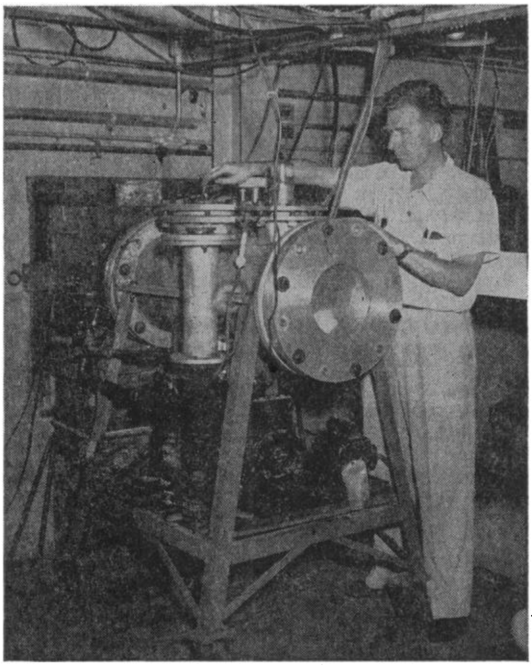

FIG. 3. Apparatus used for studying the radioactivity of the neutron. A beam of neutrons is taken from a hole in the concrete shield of the Oak Ridge reactor (background) and passes through the horizontal evacuated tank. Apparatus for counting the decay protons is inside the tank. The "bull's-eye" on the end of the tank is the thin aluminum window through which the beam emerges, to be caught finally in a heavy boron-laden, lead-shielded "beam-catcher" 10′ away.

leaves the tank through thin aluminum windows. In the vacuum, protons are presumably being formed by the decaying neutrons, and an electrostatic field is arranged so that any such protons would be accelerated in a direction perpendicular to the beam and focused upon a secondary electron multiplier which would count them. Counts are indeed observed, and this brings us to the difficult part of the experiment: How can one tell with certainty whether the counts are really coming from decaying neutrons and not from various secondary ionization processes which might be taking place because of the interaction of the gamma rays, fast and slow neutrons, and secondary electrons in the original beam with the tank walls or the residual gas in the vacuum? One rather convincing way would be to put a beta counter in the tank and look for coincidences between the beta-particles of the neutron decay and the collected protons. This is being tried, but at the moment of writing it has not given reproducible results. Another way is to work solely with the multiplier and to make subsidiary tests to see if anything imaginable besides neutron decay can be causing the counts. Thus, it is found that out of a total counting rate of about 400/min, about 100/min disappear if one does *either* of the following three things: (1) places a thin layer of boron in the beam ahead of the entrance into the vacuum; (2) places a thin foil over the entrance to the multiplier; (3) turns off the electrostatic field. Furthermore, if the boron is moved in and out of the beam while the foil is in front of the multiplier or while the electrostatic field is absent, then there is no change in the counting rate. Taken together, these observations show that the presence of the boron eliminates some positive ions of low energy which are otherwise formed in the collecting region and counted in the multiplier. These positive ions may be the decay protons; it remains to make sure. Now the predominant effect of the boron shutter is to eliminate the slow neutron component of the beam; it is too thin to affect the fast neutron component, but it admittedly may affect the secondary electron component, and it definitely will affect the the gamma-ray component by *introducing* a new source consisting of the gamma radiation emitted when it captures slow neutrons. The extent of the former of these possibilities was tested by substituting an aluminum shutter for the boron; the counting rates were unaffected by the presence or absence of the aluminum. The second possibility was tested with a radioactive pure gamma source placed at the position of the boron shutter when all neutrons were absent (reactor off). The gamma source affected the multiplier directly, but did not make positive ions, as evidenced by the insensitivity of the counting rate to the foil in front of the multiplier and to the presence of the electrostatic field. We are therefore led to the conclusion that *slow neutrons* produce the 100 counts/min of positive ions. This is what would be expected if the positive ions are decay protons, because the slow neutrons are far more dense in the beam than are the fast neutrons. However, we must still make sure that there are no processes other than neutron decay by which the slow neutrons could produce the positive ions. They are not sufficiently energetic to ionize directly, so the only mechanism would seem to be through the gamma rays (with their associated secondary electrons) excited when the neutrons are captured. To see if ionization could be taking place in the residual gas in the vacuum tank, the boron-difference counting rate was studied as the gas pressure was raised over a factor of 8; the 100 counts/min remained practically unchanged. Finally, the pure gamma source was brought up again, and it was demonstrated that for equivalent total counting rates in the multiplier, the gamma source produced very few positive ions in the collecting volume. Thus, a chain of experimental eliminations enables one to say that the observations are easily explicable on the basis of decaying neutrons, but explicable only with great difficulty on the basis of other imaginable experimental effects.

The neutron half-life can be estimated from this experiment, for the collecting and counting efficiency of the apparatus can be evaluated, and the number of neutrons in the portion of the beam under observation can be determined by foil activation measurements. The answer so far obtained is rough, but it indicates a half-life of about ½ hr, as predicted by theory.

Any one of the topics mentioned in the foregoing survey of this broad subject could obviously be greatly expanded. Also, there is much in neutron physics which we have failed to mention, as for example, the basic subject of the absolute standardization of neutron sources; a discussion of theoretical background; the interesting experiments on scattering from ortho- and para-hydrogen, and their significance in terms of nuclear forces; and the fancier aspects of slowing-down theory and experiment, such as the measurements of transport cross sections. It would also have been interesting to include a paragraph on the fascinating speculations as to the possible roles of neutrons in stellar evolution. In spite of these serious omissions, perhaps enough has been said to give the reader an impression of the range of the subject and its variety. Perhaps we have shown that Rutherford was right, particularly when he spoke of the "very novel properties" of the "atoms" which we now know as neutrons.

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